Cassini 1997 VVEJGA Trajectory Launch/Arrival Space Analysis

Steven Flanagan*
Fernando I'eralta*

The Cassini mission to Saturn, which is planned for a 1997 launch cm a Titan IV (SRMU)/Centaur, is comprised of the Huygens Titan Probe and an orbiter which will complete a four year tour of the Saturnian system. The baseline trajectory for Cassini is an Oct., 1997 VVEJGA (Venu - Venus-Ilarh-]upitcr-Gravity-Assist) trajectory. The current choice for an arrival date, June 25, 2004, provides a rare Phoebe flyby opportunity. This is significant due to the fact that Phoebe's distant orbit places it well beyond the region which will be explored by the orbiter during the tour.

The goal of this analysis is to determine the optimal feasible trajectory for any launch / arrival date combination. Trajectories have been generated for a wide range of potential launch/arrival date combinations in an effort to fully map the trajectory space. This effort has been complicated by the existence of two distinct families of solutions, which can possess substantially different characteristics for the same launch and arrival date. The characteristics and the reasons for the existence of these families arc discussed. The launch period is examined in detail, with the emphasis on finding the minimum post-launch AV trajectory solutions which fall within the capability of the launch vehicle. This analysis is used to develop a launch period utilization strategy, Finally, trajectory variations as a function of arrival date are presented.

INTRODUCTION

Cassini Mission Description

The Cassini mission, currently planned for a 1997 launch, will mark the first visit to Saturn since the landmark Voyager flybys of Saturn in 1980 and 1981. As successful as the Voyager missions were, Cassini is expected to exceed their science return by a factor of ten. The Cassini spacecraft is comprised of a Titan probe, which will be released during the initial orbit of Saturn, and an orbiter, which will perform over 30 Titan flybys and four icy satellite flybys during a four year tour.

Cassini VVEJGA Trajectory

The current baseline trajectory for Cassini is a Venus-Venus-Earth-Jupiter-Gravity-Assist (VVEJGA) launching in October 1997 on a Titan IV (SRMU)/Centaur launch vehicle. A wide range of arrival dates at Saturn is

' Member Technical Staff, Jet I'repulsion Laboratory, California institute of Technology.

possible, due to the Jupiter flyby. The current choice is June 25, 2004, which provides an opportunity for a flyby of Saturn's distant icy satellite Phoebe. The circuitous route to Saturn is necessary in order to reduce the required launch energy, or C_3, to fit within the launch vehicle's projected injection capability. The minimum C_3 required for a direct trajectory to Saturn launching in 1997 is 108 km^2/s^2. A Jupiter-C; ravity-Assist trajectory (JGA) would require a C_3 of 83 km^2/s^2. The maximum C_3 available for Cassini, assuming full propellant tanks and nominal launch vehicle performance, is approximately 22 km^2/s^2. It is only possible to launch with a higher C_3 by off loading bipropellant, an option which is shown to be a poor trade in a later section.

A reference VVEJGA trajectory, launching on Ott. 6, 1997 and arriving at Saturn on June 25,2004, is shown in Figure 1. This trajectory launches with a C_3 of 18.1 km^2/s^2 into a type 11' transfer to Venus after launch. The first Venus flyby (Venus 1) is used to place the spacecraft into a nearly resonant two Venus-year loop. Near aphelion of this loop, a large (-400 m/s) deep-space maneuver 0)SM) is performed, which lowers the perihelion of the trajectory, thereby increasing the spacecraft's V_∞ relative to Venus from 6.0 km/s at Venus 1 to 9.5 km/s at the second Venus flyby (Venus 2). This maneuver is analogous to the aphelion maneuver performed in the ΔV-Earth-Gravity-Assist (AVEGA) type trajectory. This DSM also establishes the appropriate phasing required for the next leg of the trajectory. Venus 2 sets up a very quick transfer to Earth, with a flight time of just 8 weeks. This extremely fortuitous planetary phasing eliminates the need for an additional trajectory loop in the inner solar system by imparting to the spacecraft the energy needed to reach Jupiter, where a final gravity-assist sends it on to Saturn[1-4]. -

Goals and Motivation of his Analysis

The primary goal of the Cassini launch/arrival space analysis is to determine the optimal feasible trajectory for any launch/arrival date combination. The selection of an optimal trajectory should take into account launch vehicle limitations, spacecraft AV capability and navigation considerations, Towards this end, a comprehensive database of trajectory information has been developed. This database will also facilitate increased understanding of the variation of trajectory characteristics with launch date, arrival date, and C_3. Of particular interest is the total interplanetary deterministic AV required. The Cassini project recently underwent a major redesign with the goals of reducing spacecraft mass and mission costs. As a result, the bipropellant tank size has been reduced from 4300 kg to 3000 kg. It is therefore of primary importance to determine the ΔV-optimal trajectory which is

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• A type 1 trajectory has a heliocentric transfer angle between 0° and 180°, type II is between 180° and 360°, and so on.

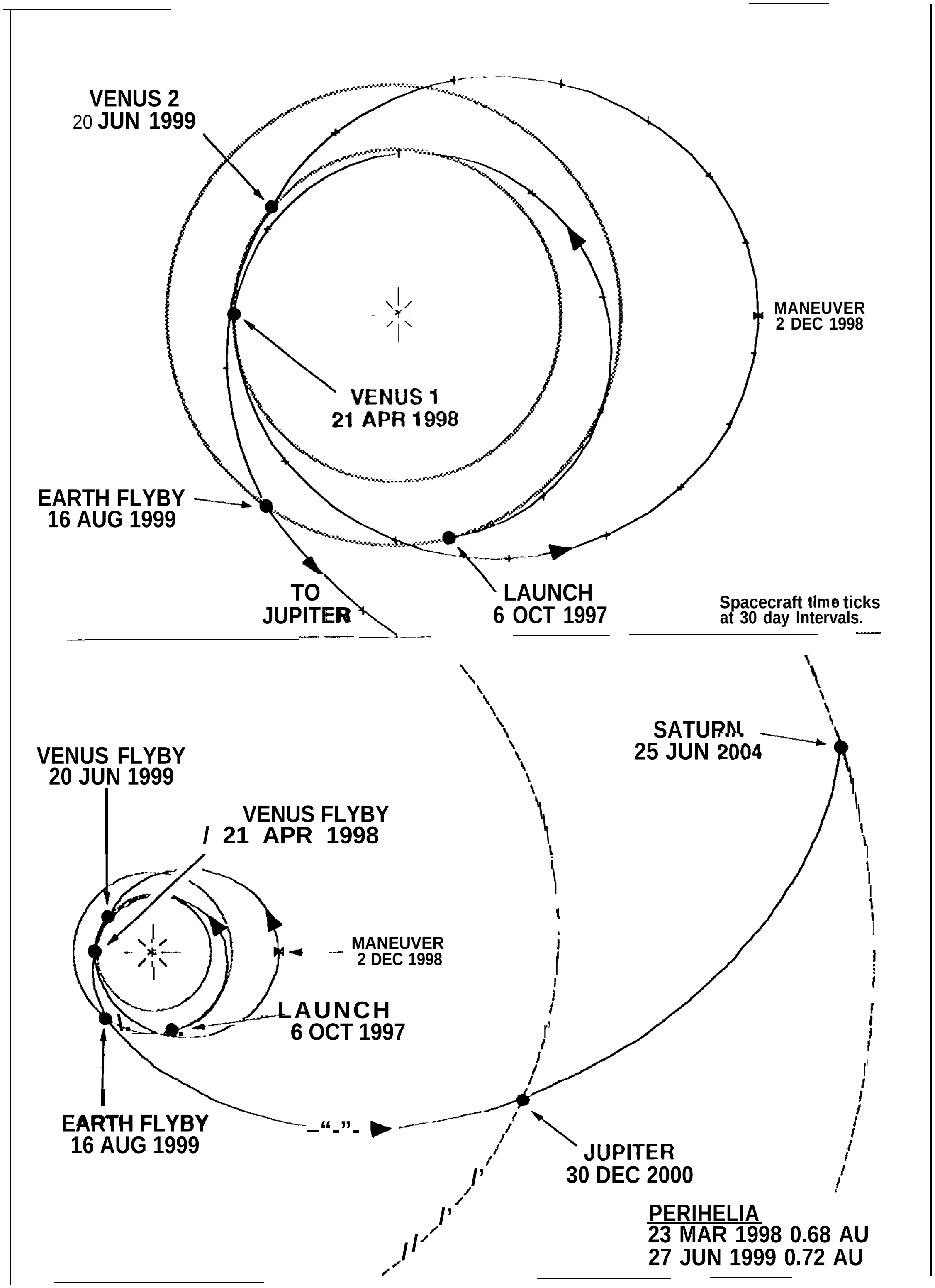

Figure 1 Cassini Oct. 97 VVEJGA, for Launch on Oct. 6, 1997 and Arrival June 25,2004. Inner Solar System and Full Interplanetary Trajectory.

within the launch vehicle performance constraints for each day of the prospective launch period.

TRAJECTORY SPACE CHARACTERISTICS

The trajectory described above and shown in Figure 1 represents the nominal Cassini VVEJGA trajectory. This was the first type of solution discovered for this trajectory. However, in the course of trying to develop a launch period for this solution, difficulties were encountered. The trajectory optimization software being used for this analysis, the multi-conic program PLATO (PLAnetary Trajectory Optimization), attempts to minimize post-launch ΔV through the manipulation of trajectory parameters. Launch energy is not included in the cost function in PLATO's normal mode of operation[1]. Beyond a launch date of Oct. 23, PLATO would start increasing the C_3 dramatically in order to reduce the post-launch ΔV. The C_3 was increased well beyond the maximum capability of the launch vehicle. This initially caused confusion, until it was discovered that another family of solutions exists for this trajectory, with much higher C_3s. By launching at a substantially increased C_3, it is possible to eliminate the large DSM between Venus 1 and Venus 2 altogether, resulting in a ballistic trajectory to Saturn. As shown in Figure 2, the higher launch C_3 is used to depress the perihelion of the trajectory initially. This results in a later Venus 1 arrival date and a Venus 1 V_∞ of 9.5 km/s. Since the Venus 1 to Venus 2 transfer is ballistic, the V_∞ at Venus 2 is also 9.5 km/s, just as in the nominal case. After Venus 2, the two types of solutions have very similar heliocentric trajectories. This second family of solutions is called the global optimum family, and the original family is called the local optimum family.

Unfortunately, the C_3s required for the global optimum solutions lie between 35 and 55 km^2/s^2. In order to launch with a C_3 of 35 km^2/s^2 using the Titan IV, it would be necessary to off load over 1100 kg of propellant. This would not leave enough propellant to perform the Huygens Probe delivery or the four year Saturn tour. Therefore, the global optimum solutions are not practical for Cassini.

However, it is possible to find useful, flyable solutions for days after Oct. 23. By fixing the C_3 to a specified value in PLATO, an intermediate family of solutions was discovered which lies between the local optimum and the global optimum families in C_3. In fact, there is a continuum of such solutions, with Venus 1 arrival dates lying between the local and global optimums and C_3s spanning the full range from 17 to 40 km^2/s^2. These fixed C_3 solutions display

[1] PLATO is generally not used until after a launch vehicle has been selected for a mission. Given this information, a trajectory will either fall within the launch vehicle performance constraints, or not. It is therefore not appropriate to include launch energy in the ΔV cost of the trajectory.

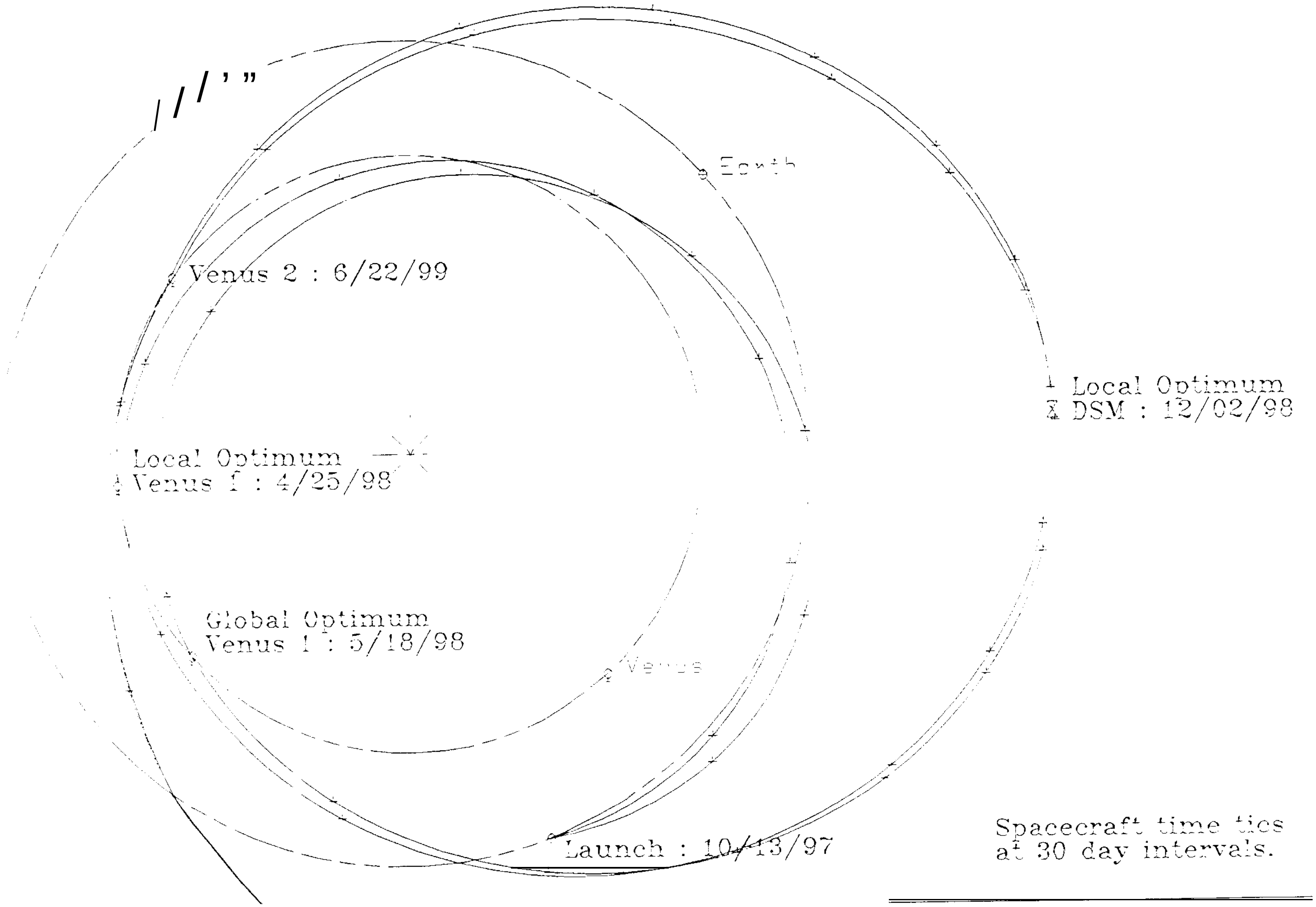

Figure 2 Cassini 10/97 VVEJGA: Local and **Global Optimums**

complicated behavior across the launch period. Depending cm the launch day and the fixed C_3 selected, an intermediate solution can resemble either the local or the global optimum family. Therefore, in addition to studying the local optimum family wherever it exists, it is also necessary to study the entire launch period at several fixed values of C_3 in order to capture these intermediate solutions,

C_3 VARIATIONS

Before trying to understand the relationships of these different types of solutions as a function of launch date, it is useful to study their behavior as a function of C_3 for a single, fixed launch day, Ott. 19. Figure 3 and Figure 4 each show curves representing three different quantities of interest:

1.) injection Margin - The difference between the maximum launch vehicle injection capability and the required injected mass.
2.) Interplanetary ΔV - Total deterministic ΔV from PLATO (not including SOI).
3.) End of Mission ΔV - Total ΔV capability of the excess propellant remaining upon completion of the nominal mission.

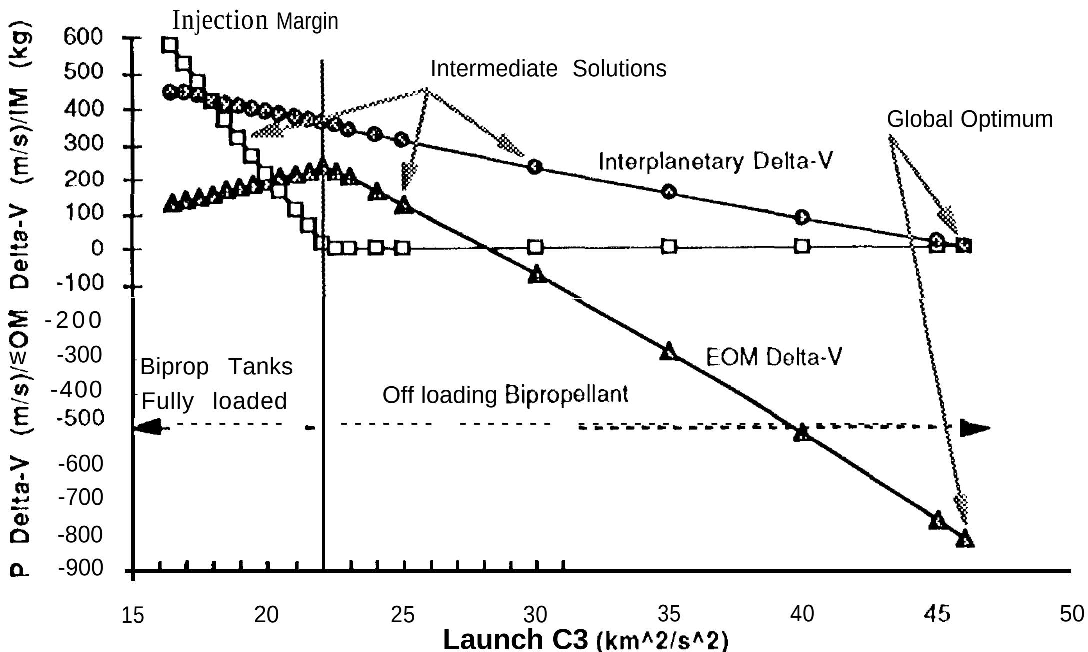

Figure 3 Injection Margin, Interplanetary Delta-V and EOM Delta-V vs C3 For Launch on 10/19/97, Arrival on 6/25/04

Figure 3 shows these curves for intermediate solutions with C_3's ranging from 16.5 km^2/s^2 up to the ballistic solution which occurs at a C_3 of 46 km^2/s^2. This chart shows, as was stated earlier, that off loading bipropellant in order to fly on a higher C_3 trajectory to reduce the post-launch ΔV is inefficient. This is because the post-launch ΔV decreases fairly slowly with increasing C_3. This is true not only for this launch day, but throughout the launch period.

Figure 4 adds the local optimum solution to the chart, and zooms in, excluding the higher C_3 intermediate solutions and the global optimum solution. The nature of the local optimum becomes apparent in this figure. The family appears as a small, parabolic curve lying at the low C_3 end of the intermediate solutions. It is this characteristic shape of the local optimum which makes it possible for the software to converge to a free C_3 solution without jumping up to the global optimum. The existence of the local optimum can most likely be attributed to the fact that the local optimum has at least one flyby on a lower bound for every day that it exists. The existence of these constraints restricts the options available to the software in its optimization, thereby limiting the number of paths that the optimization can take through the parameter space. It can therefore be impossible to reach some lower ΔV solutions due to the location of the initial guesses.

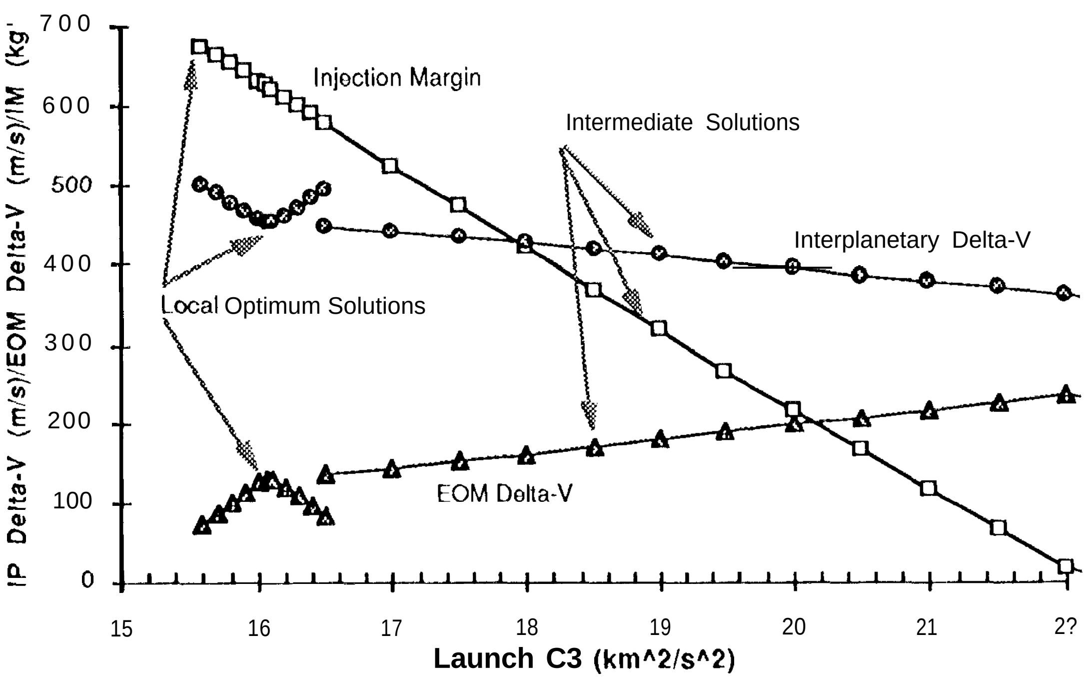

Figure 4 Injection Margin, Interplanetary Delta-V and EOM Delta-V vs C3 For Launch on 10/19/97, Arrival on 6/25/04

From Figure 5, it is clear that two distinct families do exist in this region. For C3s between 16 and 16.5 km^2/s^2, two solutions are shown, with identical C_3s and completely different flyby altitude profiles. However, it can also be seen that as the C_3 of the intermediate solution approaches the C_3 of the local optimum, its flyby altitude profile becomes *more* like that of the local optimum as well. In

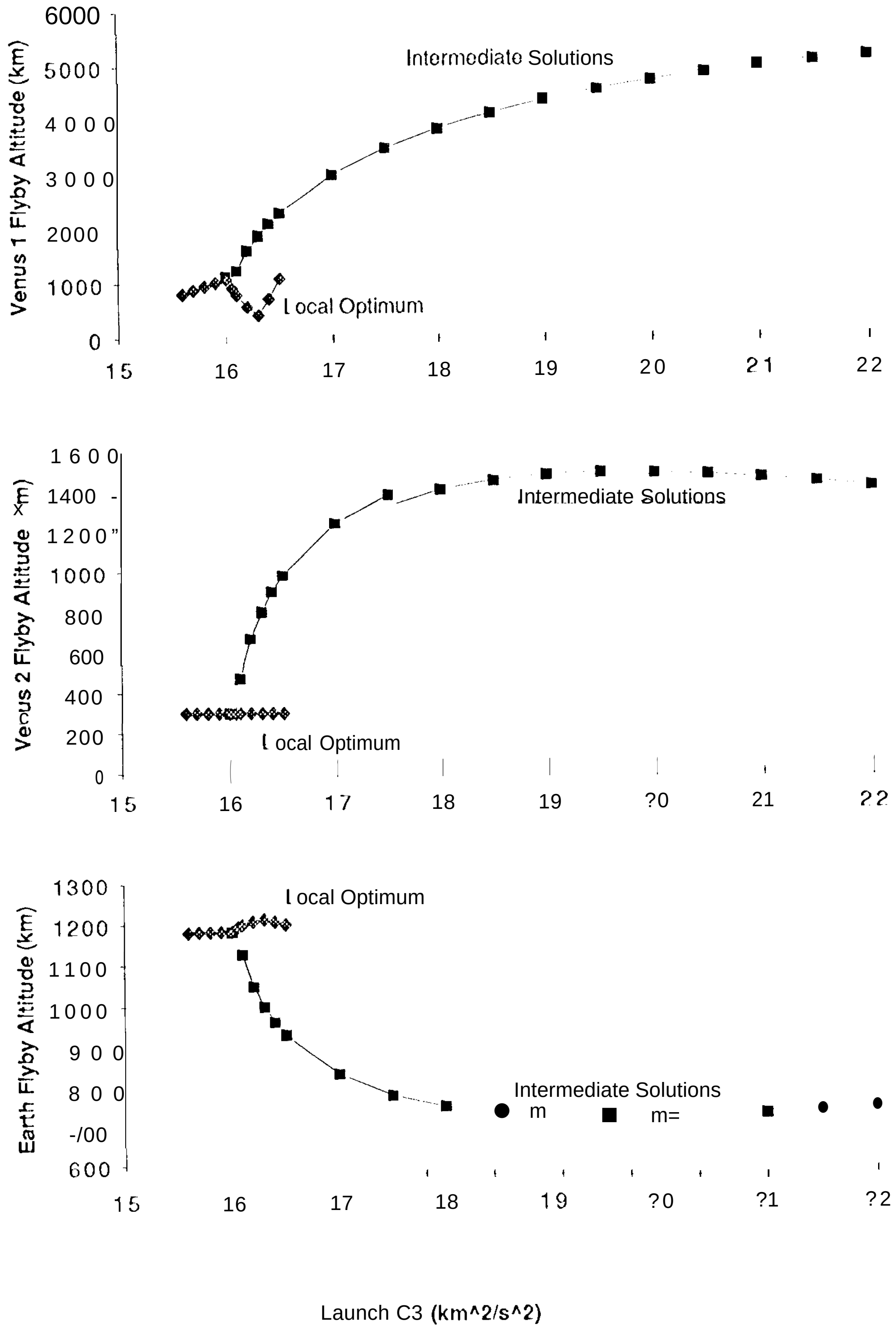

Figure 5 Venus 1, Venus 2 and Earth Flyby Altitudes vs **C3** for Launch on 10/19/97, Arrival on 6/25/04.

some sense, the intermediate solution can be said to "fall into" the local optimum as it approaches in C_3.

Looking back at Figure 3, it might seem that the best performance, as judged by EOM **ΔV, will** always occur at the point where the injection margin goes to zero. This appears to be so due to the fact that for this launch day a very small increase in C_3 along the intermediate solution is all that is required to provide an improvement in performance over the local optimum, and further increasing the C_3 continues to yield better performance until the maximum launch vehicle capability is reached. In other words, the neighborhood for which the local optimum is optimal is very small. This is not always the case, however, as will be demonstrated when other launch days are considered.

LAUNCH PERIOD ANALYSIS

Although Cassini's nominal launch period is only 25 days long, extending from Oct. 6 to Oct. **30, the** launch date portion of this analysis examined a range of launch dates covering 41 days, from Sept. 27 to Nov. 6, in two day increments. All of the data shown in this section was computed for an arrival date of June 25, 2004. As expected, the characteristics of the VVEJGA trajectory, such as flyby altitudes, flyby dates and DSM magnitudes and times, vary greatly with changes in launch date. The local optimum trajectories, which exist for launch days from Sept. 27 to Oct. 23, have C_3s which range from 15.9 to 19.9 km^2/s^2. In addition, the intermediate solutions were studied over the entire range of launch dates at fixed C_3s of 18, 20 and 22 km^2/s^2. To simplify the analysis, the range of launch dates studied is broken up into three regions based on the performance of the various families, as shown in Figure 6*. In the following paragraphs, the behaviors of each of the families of solutions (local optimum, global optimum and intermediate) will be described for each region. This information will then be used to formulate a strategy for the nominal launch period.

Sept. 27 to Oct. 10

The first region extends from Sept. 27 to approximately Oct. 10, and is defined by the fact that for launch days in this period, the local optimum family provides the best performing (lowest post-launch **ΔV)** trajectories that lie within the capability of the launch vehicle. The local optimum family in this region is characterized by the fact that the Venus 1 flyby is always on the lower bound of 300 km*.

* The breaks in the curves in Figures 6, 6a, 7, 8 and 9 represent points where a flyby either goes on to or comes off of an altitude bound.

* For the purposes of this study, flyby altitudes are constrained to remain above 300 km in order to prevent damage to the spacecraft and to increase navigation safety. Since the time at which these data were generated, the minimum Earth flyby altitude has been raised to 500 km.

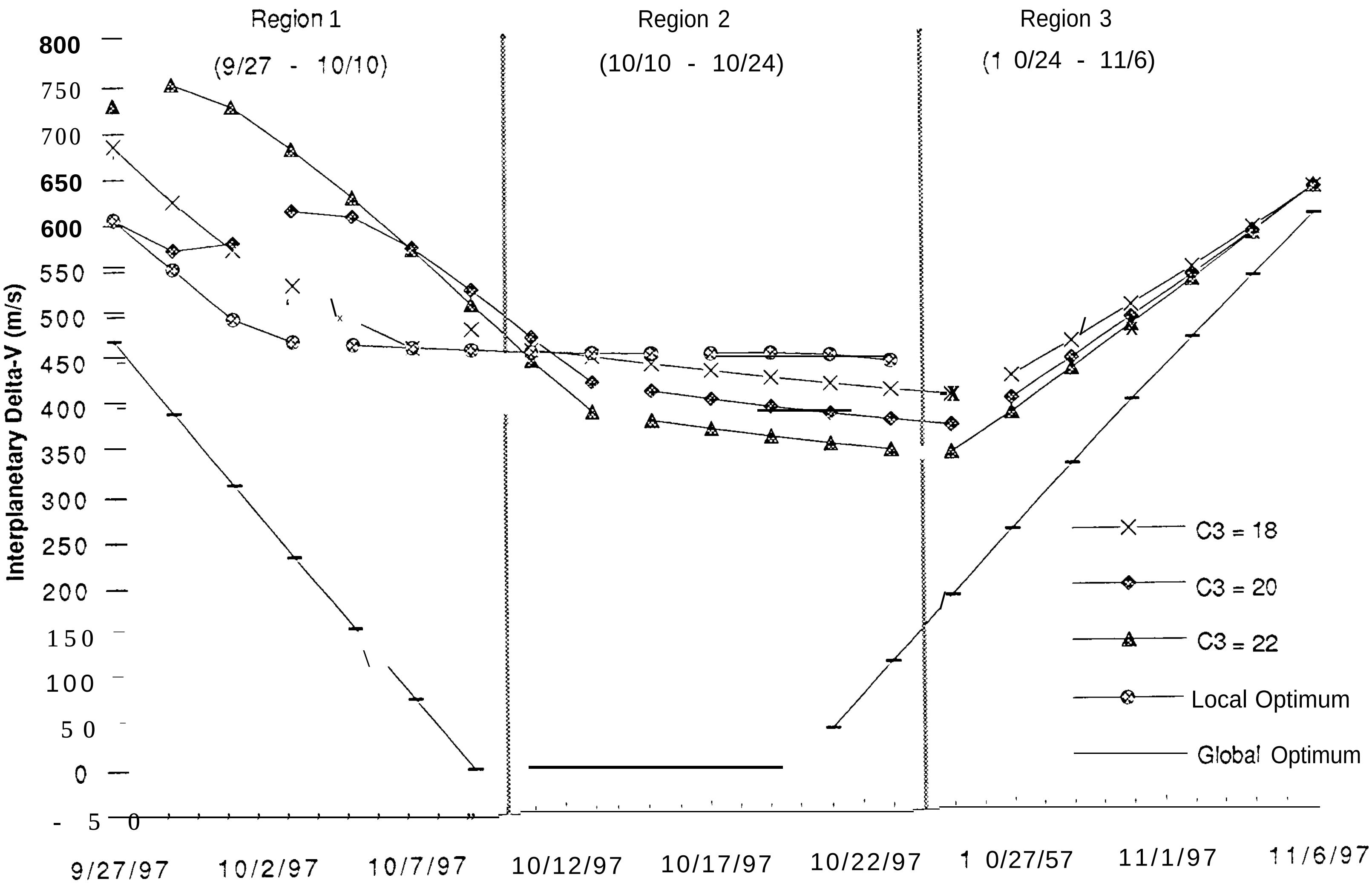

Figure 6 Interplanetary Delta-V (not including SOI) vs Launch Date for Local Optimum, Global Optimum and Intermediate SolutionsofC3=18, 20 and 22.

The global optimum trajectories are ballistic for only a very small portion of this region, On most launch days, a maneuver is required for these trajectories between launch and Venus 1, due to the fact that the Earth flyby altitude is on the lower bound of 300 km. The maneuver is required in order to compensate for the loss in gravity assist bending that results from being constrained to perform the flyby at an altitude higher than the optimum.

The intermediate solutions usually require a maneuver between launch and Venus 1 during this period as well, in addition to the large maneuver between Venus 1 and Venus **2. This is** also due to the fact that the Earth flyby is on the bound. The intermediate solutions are undergoing a transition in this region, which accounts for the intersections of curves in Figures 6 and 6a. As was demonstrated previously, the intermediate solutions will tend to be similar to the local optimum when they are close to the local optimum in C_3*. All of the

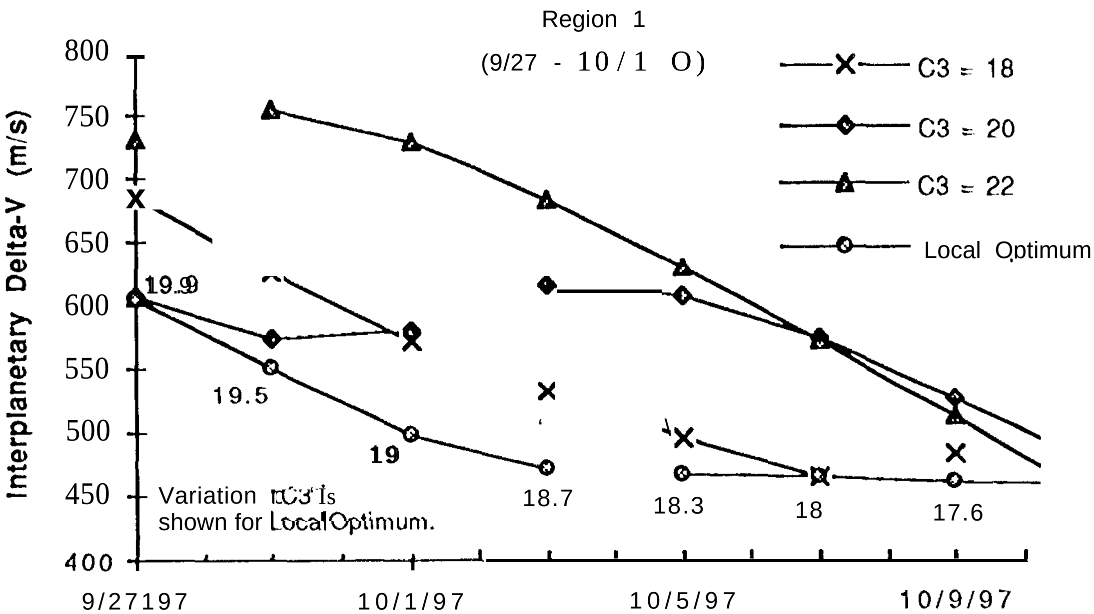

Figure 6a Interplanetary Delta-V (not Including SOI) vs Launch Date for Local Optimum and Intermediate Solutions of C3=18, 20 and 22 for Region 1.

fixed C_3 curves resemble the local optimum on Sept. 27, where the local optimum has its highest C_3. As the C_3 of the local optimum falls, the intermediate solutions make the transition to become similar to the global optimum. The fixed C_3 of 18 solution will be used to illustrate this behavior. On Sept. 27, the Venus 1 flyby altitude for this solution is on the lower bound, similar to the local optimum, as shown in Figure 7. Figures 8 and 9 show that the Venus 2 and Earth

*In this context, similarity between solutions refers primarily to flyby altitude profiles, since the families tend to be characterizable in terms of these profiles. The same arguments could be made in terms of flyby dates.

flyby altitudes are also close to the local optimum'. The post-launch AV of the C_3 of 18 solution, shown in Figure 6a, is -80 m/s higher than the local optimum. What this suggests is that the C_3 of 18 solution is like the local optimum solution in this region, but is displaced from the local optimum in C_3. In other words, if the local optimum family is thought of as a parabolic curve in the C_3 vs. Interplanetary AV plane (see Figure 4), then the C_3 of 18 solution for this launch date lies cm this curve, but offset from the minimum value. This is because the local optimum solution has a C_3 of 19.9 km^2/s^2 on Sept. 27. But as you move forward through the launch period, the local optimum C_3 falls, hitting 18 on Oct. 7. Notice in Figure 6a that for **this launch** day, the C_3 of **18** solution and the local optimum have identical post-launch AV. Oct. 7 is the last launch day for which the C_3 of 18 solution has the Venus 1 flyby on the lower bound. After this launch day, the solution starts to look more like the global optimum solution, as the C_3 of the local optimum continues to fall. Each fixed C_3 solution displays a similar behavior in this region, The onset of the transition to the global optimum coincides with the Venus 1 flyby coming off of the lower bound.

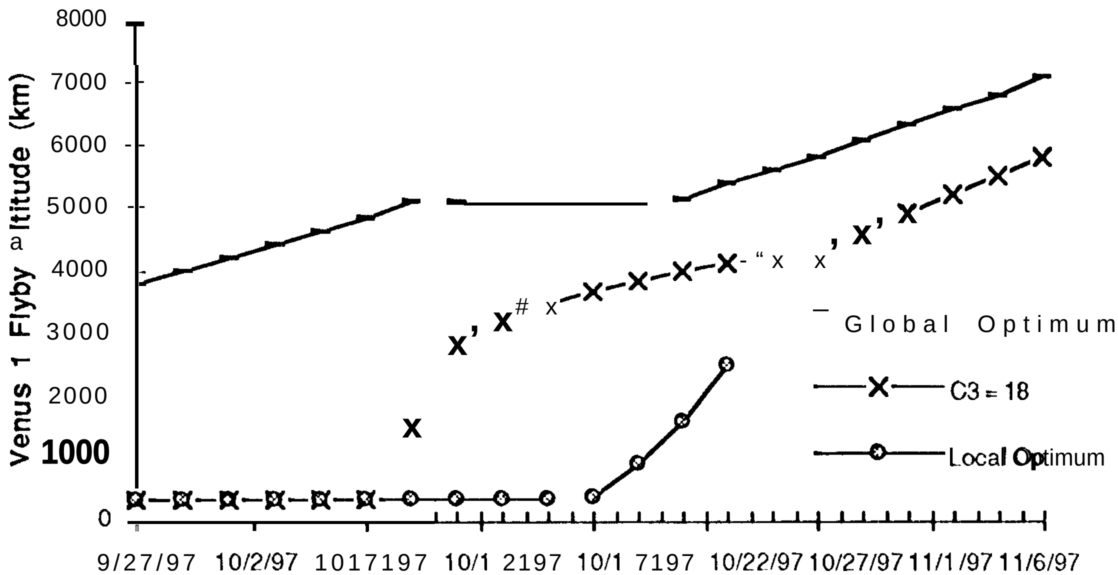

Figure 7 Venus 1 Flyby Altitude vs Launch Date

Ott. 10 to Oct. 24

In this region, the local optimum still exists, but is only locally optimal for a very small neighborhood, An increase in C_3 of 1 or 2 points is all that is needed

' The Venus **2** and Earth flyby altitudes are also similar to the global optimum cm Sept. **27.** For this launch day, the different solutions are distinguished primarily by their Venus 1 flyby altitude.

to reach a lower post-launch ΔV solution. In fact, it is somewhat surprising that the software is able to converge to a solution for the local optimum at all in this region, It is only able to do so on those days for which the flyby altitude profiles of the local optimum and the intermediate solutions are distinct. Figure 8 shows that the Venus 2 flyby altitude of the local optimum is on the lower bound starting on Oct. 17. Through Oct. 23, the Venus 2 flyby altitude of the intermediate solutions, again represented by the C_3 of 18 curve, is well above this bound. This difference is sufficient for the software to be able to distinguish between the two types of solutions, given appropriate initial guesses. After Ott. 23, however, both types of solutions have Venus 2 on the bound. Also, looking back at Figure 7, by Ott. 23 the Venus 1 flyby altitude of the local optimum has climbed towards the intermediate solutions. As a result of this increasing similarity between the local optimum and the intermediate solutions, the higher C_3 solutions are now less and less distinguishable from the. local optimum. Hence, if the C_3 is left as a free variable, it will be increased until the now ballistic global optimum solution is reached. Therefore, the local optimum solution no longer exists as a distinct family beyond a launch date of Ott. 23.

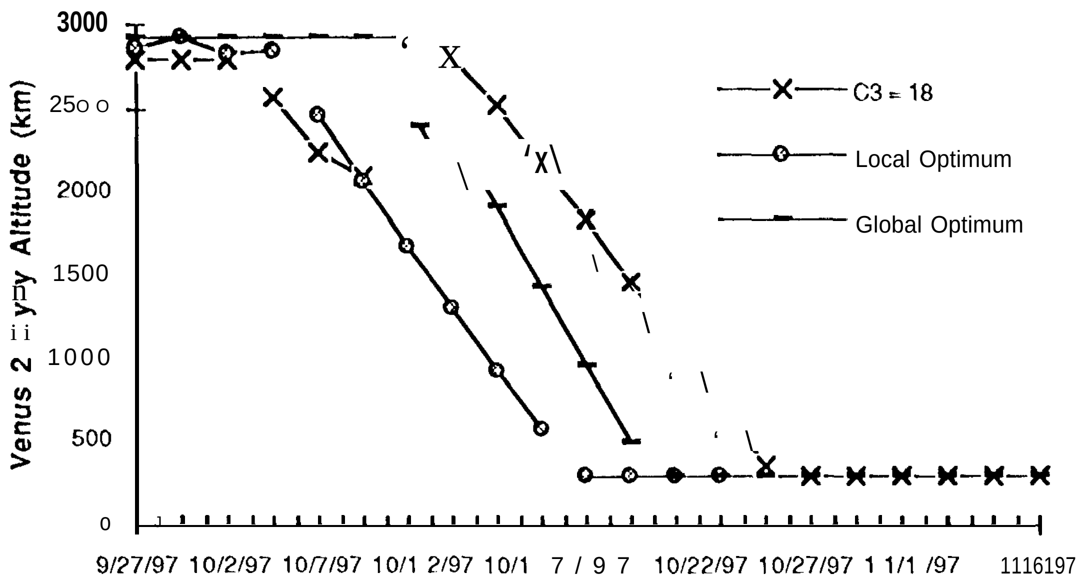

Figure 8 Venus 2 Flyby Altitude vs Launch Date

The global optimum solutions are ballistic for the majority of this region. This is a result of the fact that the flybys for the global optimum solution are unconstrained for these days. However, on Ott. 21. the global optimum again begins to require a maneuver, this time due to the Venus 2 flyby altitude hitting a constraint. This foreshadows the behavior of the intermediate solutions, which are now quite similar to the global optimum.

It is in this region that the intermediate solutions begin to become interesting for more than academic reasons. Starting on Ott. 13, these solutions enter a region where they are completely unconstrained, i.e., none of the flybys are on lower bounds. This results in substantially improved performance as compared to the local optimum. For example, on Ott. 19, it is possible to save -90 m/s of AV by launching at a C_3 of 22 km^2/s^2 instead of the local optimum value of 16.

Oct. 24 **to Nov.** 6

The local optimum has now disappeared, for the reasons noted earlier.

The intermediate solutions now represent the only useful set of solutions for Cassini. Starting on Oct. 25, however, the trajectories once again require a DSM on the launch to Venus 1 leg. This is due to the Venus 2 flyby altitude hitting the lower bound. This maneuver grows rapidly, and causes the overall performance of the solutions to deteriorate.

The global optimum follows a similar pattern, with the maneuver that appeared on Oct. 21 increasing steadily.

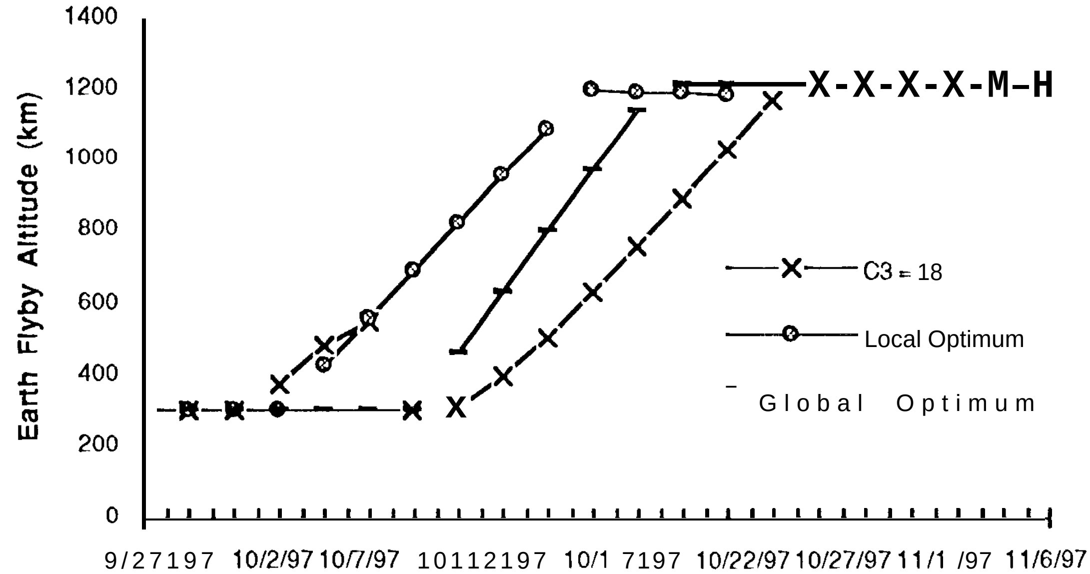

Figure 9 Earth Flyby Altitude vs Launch Date

Summary of Variations clue to Launch Date and C_3

Figure 10 represents an attempt to illustrate all of the points made thus far concerning launch period and C_3 variations in one figure. The key concepts that should be noticed in Figure 10 are the following:

1.) interplanetary ΔV is lowest in the middle of the launch period, and rises at either end, due to flyby altitudes hitting constraints.
2.) The local optimum solutions, represented by the small parabolic surfaces in the forefront of the figure, provide the best available performance at the beginning of the launch period, then disappear towards the end.
3.) The C_3 of the local optimum solutions varies as a function of launch date.
4.) The intermediate solutions provide the best performance starting in the middle of the launch period and continuing until the end.

Launch Period Strategy

The first goal of the launch period strategy for the Ott. 97 VVEJGA is to define reasonable boundaries for the launch period. Cassini has a project requirement that the nominal launch period extend for at least 18 days. However, Cassini's backup trajectory is a VEEGA (Venus-Earth-Earth-Gravity-Assist) launching in 1999, which arrives at Saturn in December of 2008. It is crucial, therefore, to have the longest launch period possible, to ensure that the launch opportunity is not missed. Both the open and close of Cassini's launch period are determined by interplanetary ΔV performance, rather than by launch ΔV. As it turns out, the selection of both the open and close dates are strongly influence by flyby altitude constraints.

The selection of the opening day of the launch period is crucial. The data from previous planetary missions suggests that there is a very good likelihood of launching on this day. It is important, therefore, to pick a day which has acceptable characteristics, For Cassini, the most significant characteristics are performance and Earth flyby altitude, Although a minimum flyby altitude of 300 km was allowed in generating the data for this study, recent analysis has suggested that, for this trajectory, a minimum Earth flyby altitude of 500 km is preferable. As shown in Figure 9, the local optimum solutions, which have the best performance for the early portion of the launch period, don't have an Earth flyby as high as 500 km until Ott. 6. Although it is possible to constrain this flyby to be at 500 km for days earlier than the 6th, this results in a substantial] performance penalty*. Therefore, Oct. 6 was selected as the opening clay of the launch period.

* Not surprisingly, the penalty for constraining the Earth flyby to be 500 km increases as you move to earlier launch clays. On Oct. 5th, the penalty is not yet severe. Therefore, it is conceivable that the open of the launch could move one m two days earlier if it was felt that a longer launch period was needed.

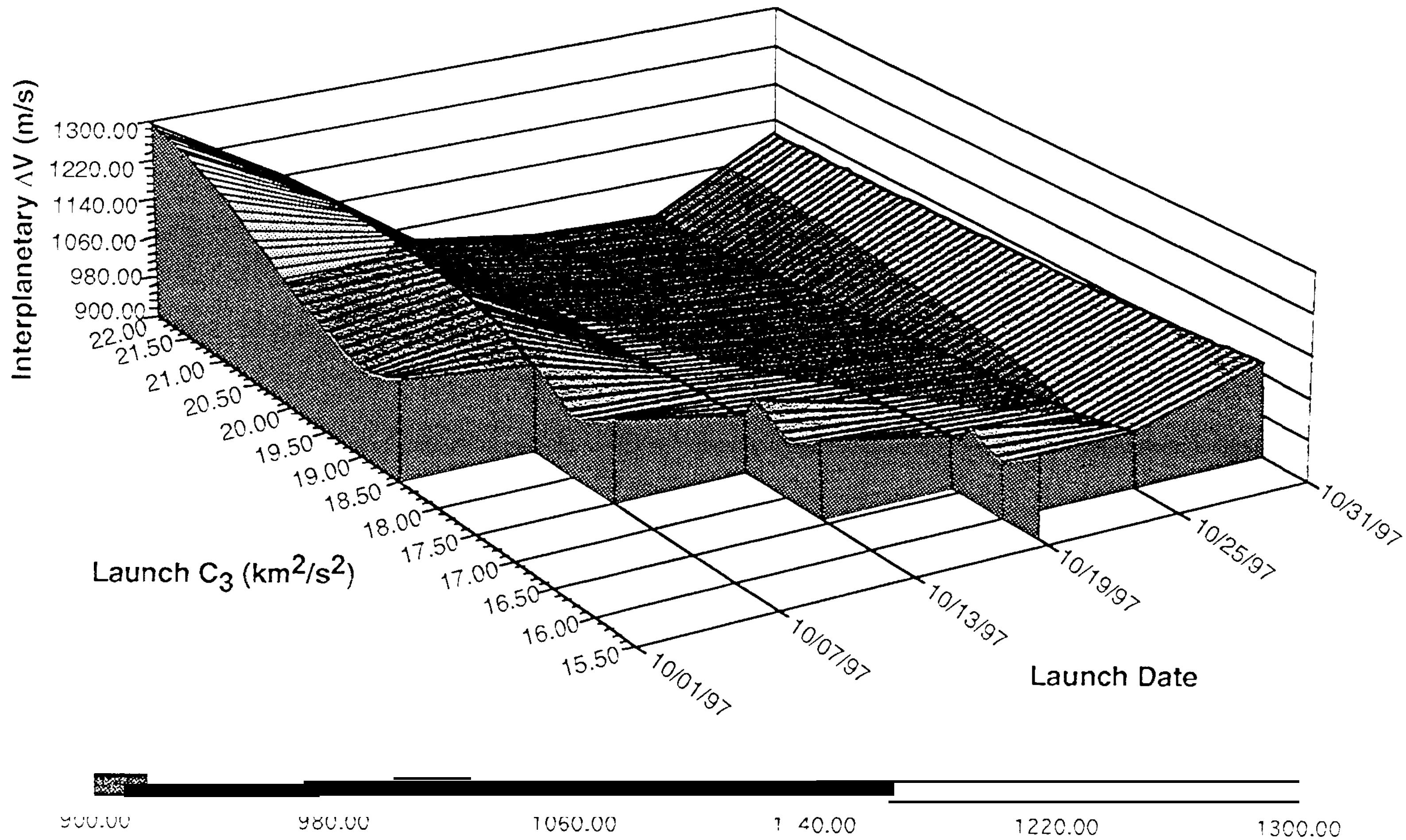

Figure Interplanetary ΔV as a Function of Launch Date and C_3

As can be seen in Figure 6, the performance of the intermediate solutions at the end of the range of days studied is getting rapidly worse. This is due, as mentioned previously, to the appearance of a maneuver on the launch to Venus 1 leg of the trajectory. This maneuver appears as the result of the Venus 2 flyby hitting the lower bound of 300 km and warrants some special consideration due to its location. The maneuver occurs approximately one month prior to Venus 1, at a time when the spacecraft is inside .7 AU, nearly at perihelion. This is a strenuous thermal environment. The spacecraft will be sun-pointed on this leg of the trajectory, using its high gain antenna to shield itself from the sun. However, in order to perform a maneuver, it is necessary for the spacecraft to rotate off of sun-point. The amount of time, and hence the size of the maneuver, for which this is possible without damage to the spacecraft is limited. Currently it is estimated that the largest maneuver possible without violating thermal constraints is around 100 m/s*. The maneuver approaches this value on Oct. 30, marking the end of the nominal launch period.

The existence of the different families of solutions complicates the launch period strategy somewhat. It is not enough to have fixed the open and close of the launch period; now it is necessary to decide which solution to use for each day in the launch period. Based on the performance information shown in Figure **6,** it is clear that the local optimum solution will provide the best performance for the opening days of the launch period. These solutions will therefore be used at the opening of the launch period, starting on Oct. 6. However, it is obvious that at some point it will be necessary to switch to the intermediate solutions, since the local optimum solution disappears after Oct. 23. Based purely on performance, Figure 6 suggests that the intermediate solutions should be used for all launch days subsequent to Oct. 11. However, it is unlikely that this will be the case in practice. As can be seen in Figure 9, the Earth flyby altitude for the intermediate solutions doesn't climb above 500 km until after Ott. 15. Again, it is possible to constrain the flybys to remain above 500 km, but performance suffers as a result, Therefore, it is likely that the intermediate solutions will be used starting on or near Oct. 15 and for all subsequent dates.

The final unknown is the fixed value of C_3 to use for the intermediate solutions once the transition has been made. The final decision on this question will not be made until the launch vehicle performance is known more precisely. It is likely that the value will lie somewhere between 18 and 22 km^2/s^2. Clearly, its is desirable to launch at the highest C_3 possible, in order to minimize the AV requirements. However, it is also prudent to carry some injection margin at

*There are two ways in which the maximum possible size of this maneuver can be increased. It is possible to force the maneuver to occur at a mm-optimal point between launch and Venus 1, or the maneuver can be broken up into segments. Both of these techniques would incur some AV penalty.

launch, as a hedge against potential performance shortfalls'. The final C_3 value chosen will represent a trade between these two concerns.

ARRIVAL DATE ANALYSIS

As mentioned previously, Cassini's nominal arrival date, June 25, 2004, was selected because it provides an opportunity for a Phoebe flyby. Cassini will never have an opportunity to perform a close flyby of Phoebe during the four-year tour since Phoebe's distant orbit around Saturn places it well outside Cassini's apoapses. Phoebe is of particular interest to astronomers due to questions concerning its origin. These factors combine to make it highly desirable to maintain the nominal arrival date.

However, more important than maintaining the nominal arrival date is guaranteeing a launch during the Oct. 97 opportunity. The penalty for missing this launch opportunity is severe. Therefore, any alternatives that have the potential to make a launch in Oct. 97 more likely must be explored. For example, reducing the required total ΔV might be necessary in order to respond to spacecraft mass increases. Extending the flight time is one of the few means by which this sort of mission resiliency can be provided. The ΔV savings is almost entirely in the SOI maneuver. The inner solar system segments of the trajectory require complex phasing, in effect "pinning down" the trajectory, and are affected only slightly by changes in the flight time.

The size of the SOI maneuver is determined primarily by two factors: the incoming V_∞ at Saturn and the period of the initial orbit into which the spacecraft is inserted. As can be seen in Figure 11, a longer flight time is achieved by a closer flyby at Jupiter, which results in more bending of the trajectory. The increased bending at Jupiter causes a more nearly tangential approach to the rendezvous with Saturn, as shown in Figure 12. This reduces the incoming V_∞, and therefore reduces the size of the SOI maneuver. Figure 13 demonstrates this graphically.

Extending the flight time can also potentially have an impact on the duration of the launch period. It was previously explained that the open of the launch period is strongly influenced by the fact that the Earth flyby altitude is on the lower bound of 500 km for all days prior to Oct. 6 for the nominal arrival date of June 25, 2004. Moving the arrival date approximately one year later, to June 10,2005, causes the Earth flyby to come off of this bound nearly 5 days earlier. It is not possible, however, to move the close of the launch period by changing the

•During the earl y stages of a mission, substantial launch vehicle margins are carried by the launch vehicle community. As launch approaches, these margins will either be used up or released. At launch, any margin remaining is, by definition, injection margin.

arrival date. The maneuver that appears at the end of the nominal launch period displays very similar behavior across the range of arrival dates studied.

in an effort to combine the launch period analysis with the arrival date analysis, Figure 14 has been constructed as representative of a potential Launch Date/Arrival Date strategy. Figure 14 shows the Total AV required as a function of Launch Date and Arrival Date. Also, an attempt has been made to represent the transitions from the local optimum solutions to the global optimum solutions. This transition will tend to take place at a different point in the launch period for different arrival dates. A fixed C_3 of 22 km^2/s^2 was used for the intermediate solutions.

In summary, two effects of extending the flight time to Saturn have been identified which could potentially increase the likelihood of successfully launching during the Oct. 1997 VVEJGA opportunist y. It is possible to reduce the required total AV of the mission and it is possible to increase the duration of the nominal launch period substantially. The potential benefits of a longer flight time will have to be weighed against the loss of the highly desirable Phoebe flyby that is available for the June 25,2004 arrival date.

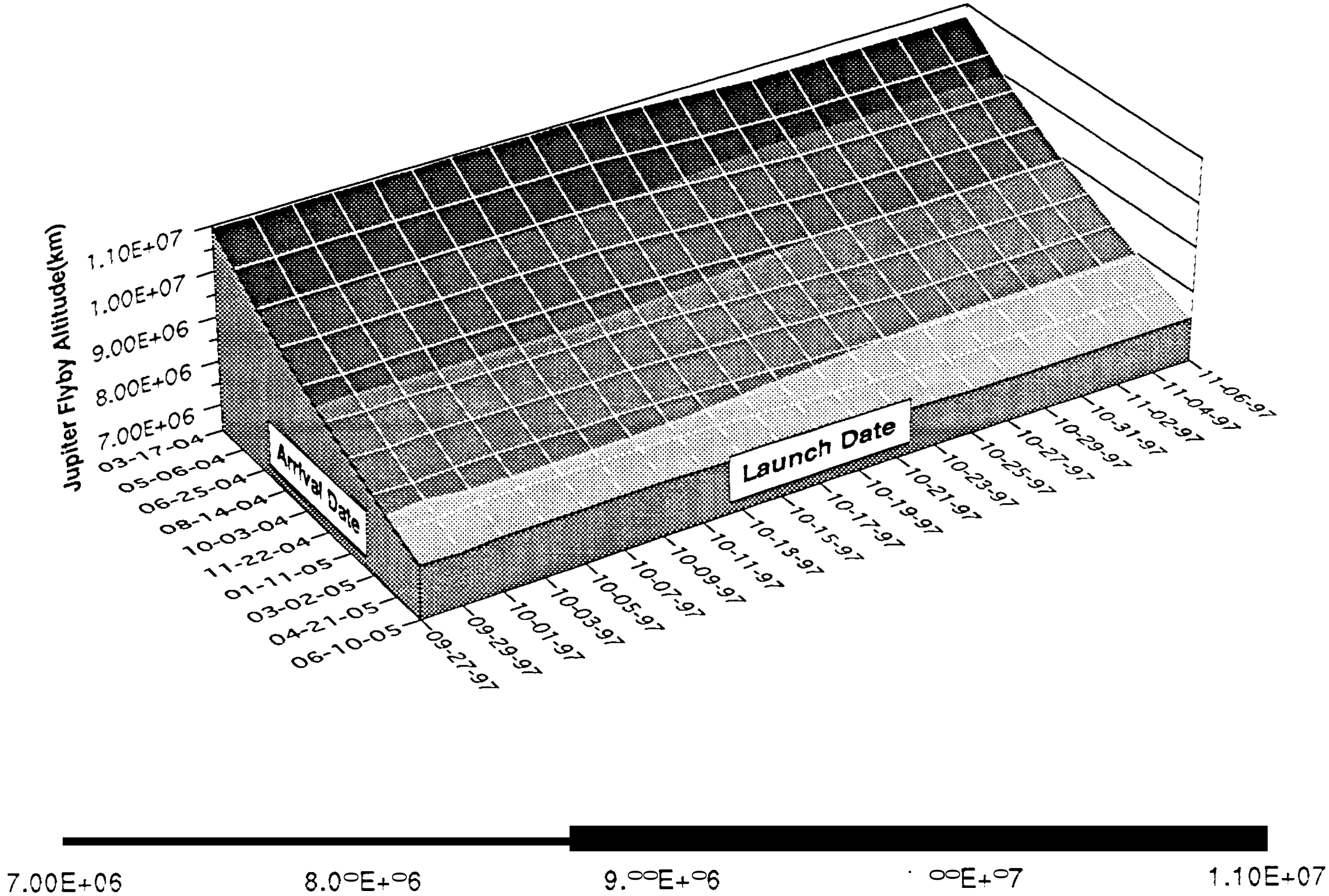

Figure 11 Jupiter Flyby Altitude vs Launch Da e and Arrival Date for a Fixed C3 of 22 km^2/s^2.

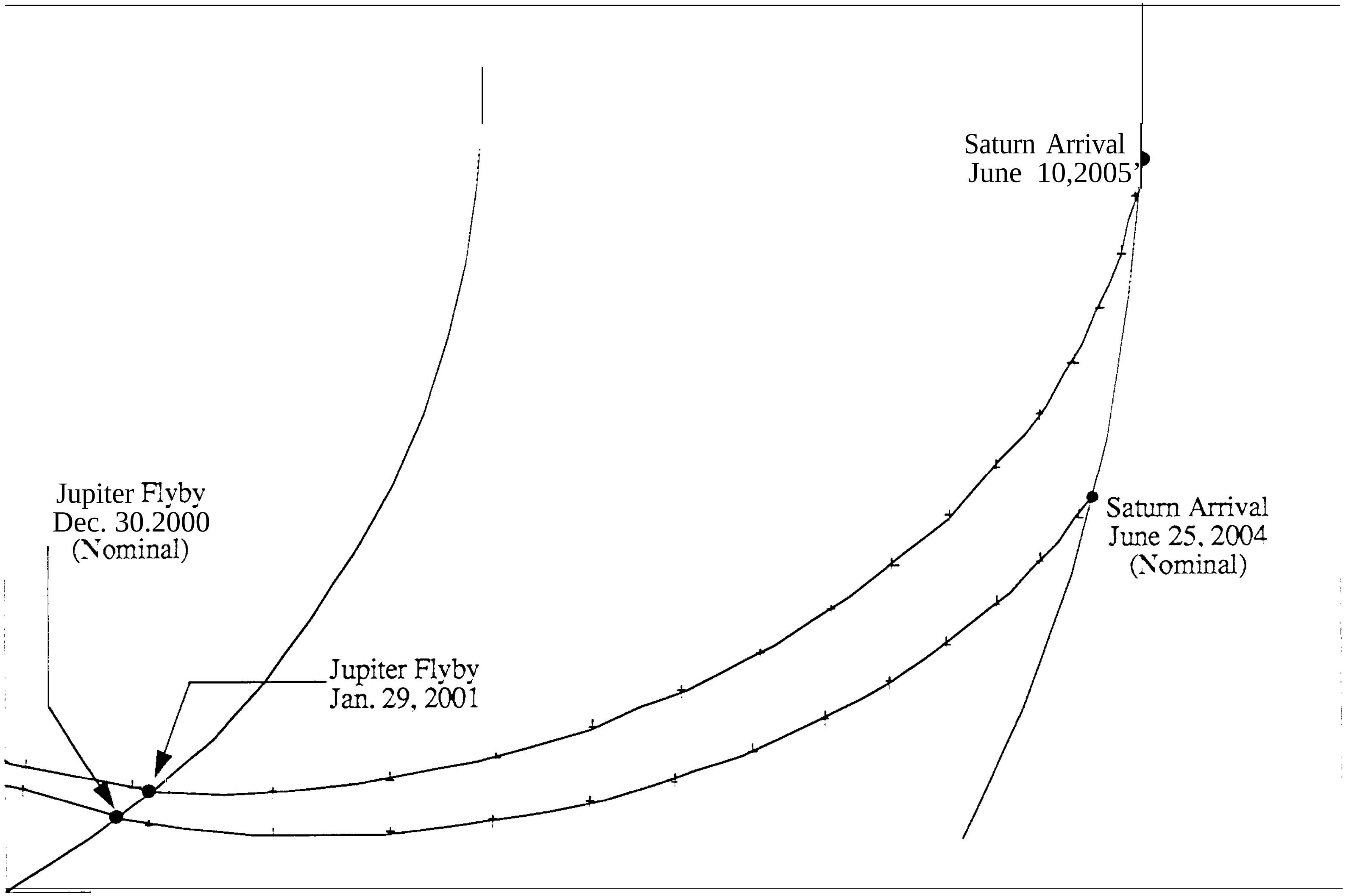

Figure 12 Jupiter to Saturn Leg for Nominal Arrival Date and June 10,2005 Arrival Date

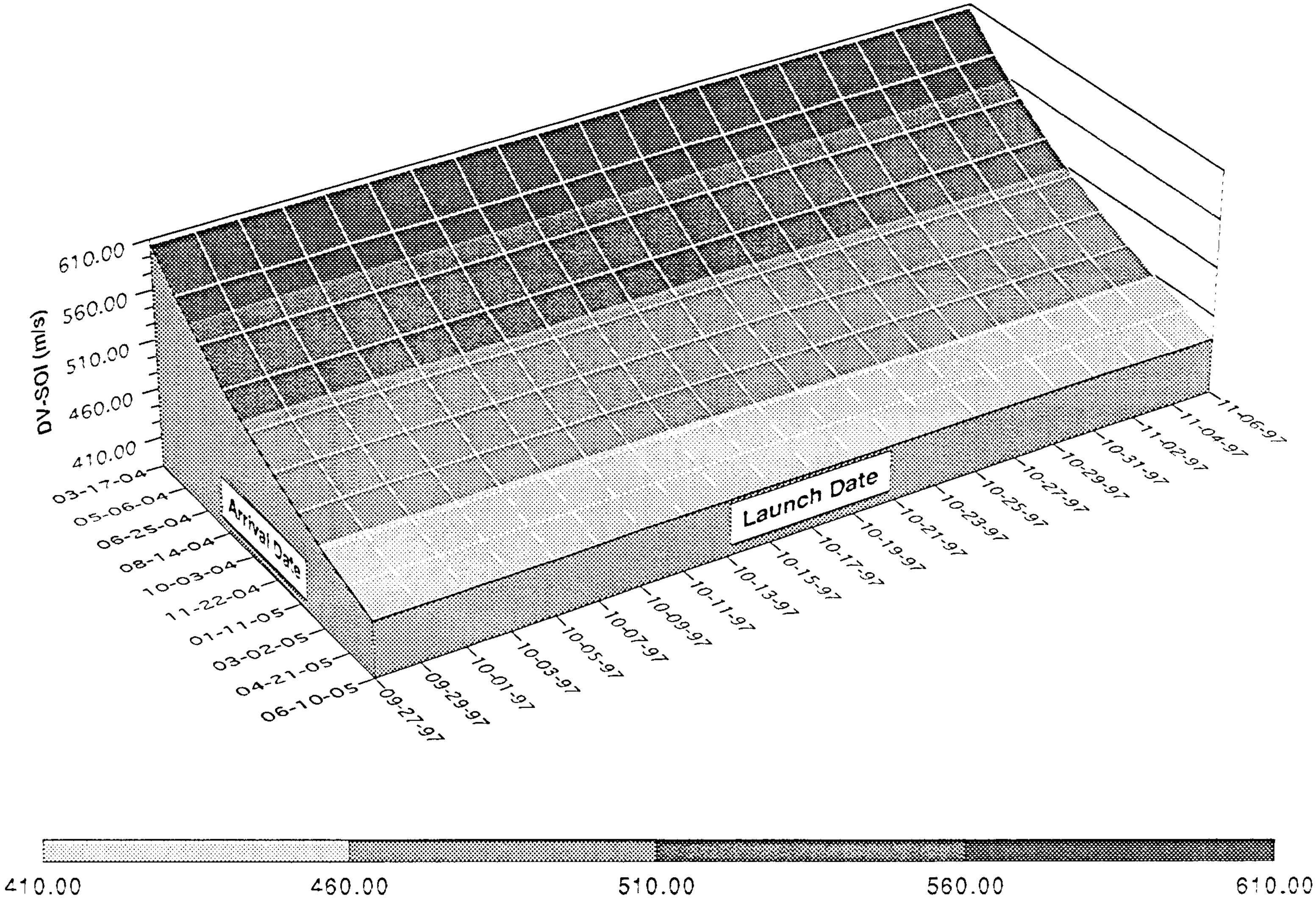

Figure 13 SOI Delta-V vs Launch Date and Arrival Date for a Fixed C3 of 22 km^2/s^2.

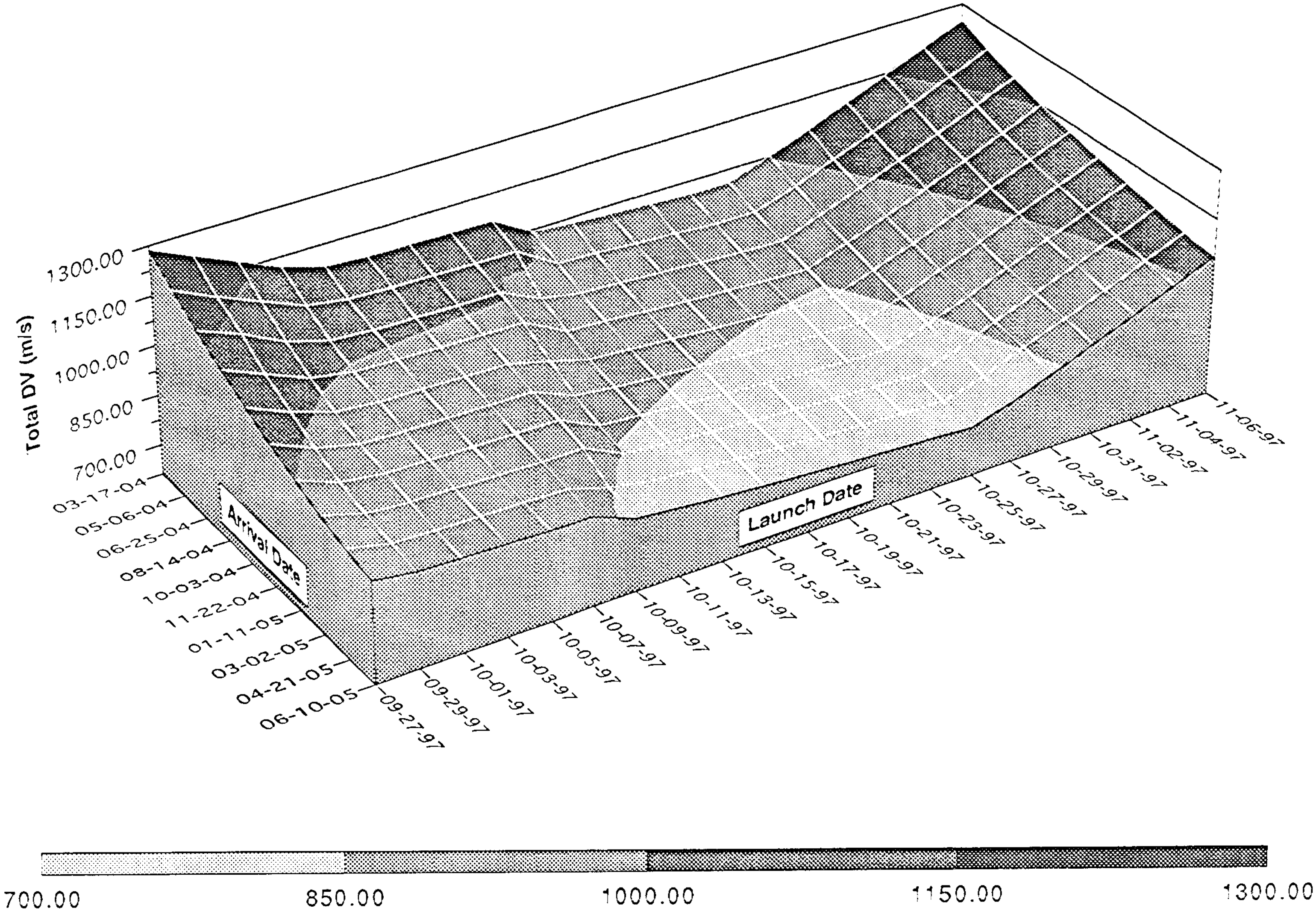

Figure 14 Total Delta-V (including SOI) vs Launch Date and Arrival Date for C3 = 22 **km^2/s^2** and Local Optimum.

CONCLUSION

The launch/arrival space for the Oct., 1997 VVEJGA trajectory to Saturn has been analyzed. Two distinct families of solutions have been found. The first is a local optimum family with C_3s ranging from 19.9 to 15.9 km^2/s^2 for the launch days studied. Solutions in this family all have a large AV **between** Venus 1 and Venus 2. The second family is a globally optimum family, which launches at a C_3 of between 35 and 55 km^2/s^2. On some launch days, these solutions are ballistic, requiring no deterministic interplanetary AV, while on other launch days a maneuver is required between launch and Venus 1. Due to the fact that the local optimum is the best feasible trajectory for only a subset of the launch period, intermediate solutions, which have C_3s that lie between the local and global optimums, have been generated, which will be used on launch days for which they provide superior EOM AV performance.

Variations in arrival date are accomplished primarily by altering the Jupiter flyby altitude, A closer flyby at Jupiter results in greater bending, and a later arrival at Saturn. In addition, the SOI AV decreases with increasing arrival date, due to the fact that the spacecraft's approach to Saturn is becoming more nearly tangential, reducing the V_∞. It is therefore possible to reduce the required AV by extending the flight time, Also, it is possible to extend the nominal launch period for later arrival dates, increasing the likelihood of a successful launch. The nominal arrival date of June 25, 2004, is considered the most likely arrival date however, since it provides a Phoebe flyby opportunity.

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